

# **High-Frequency Sound Interaction in Ocean Sediments**

Eric I. Thorsos

phone: (206) 543-1369 fax: (206) 543-6785 email: [eit@apl.washington.edu](mailto:eit@apl.washington.edu)

Kevin L. Williams

phone: (206) 543-3949 fax: (206) 543-6785 email: [williams@apl.washington.edu](mailto:williams@apl.washington.edu)

Darrell R. Jackson

phone: (206) 543-1359 fax: (206) 543-6785 email: [drj@apl.washington.edu](mailto:drj@apl.washington.edu)

Dajun Tang

Applied Physics Laboratory

University of Washington

Seattle, Washington 98105

phone: (206) 543-1290 fax: (206) 543-6785 email: [djtang@apl.washington.edu](mailto:djtang@apl.washington.edu)

Award Number: N00014-98-1-0040

<http://www.apl.washington.edu/hfsa-dri/index.html>

## **LONG-TERM GOAL**

Our long-term goal is to develop accurate models for high-frequency scattering from, penetration into, and propagation within shallow water sediments. Reaching this goal requires a better understanding of several fundamental issues pertinent to high-frequency sediment acoustics. These issues include an understanding of the dominant scatterers versus frequency near the sediment surface, the potential need for poroelastic sediment models, the appropriateness of stochastic descriptions of sediment heterogeneities, the importance of single versus multiple scattering in sediments, and an understanding of the physical and biological processes that determine sediment structure.

## **OBJECTIVES**

We have five specific objectives. First, identify the dominant backscattering mechanisms (20-300 kHz) and demonstrate that the backscattered field can be quantitatively modeled based on measured sediment properties (20-50 kHz). Second, identify the dominant subcritical penetration mechanisms in sandy sediments and demonstrate that the penetrating field can be quantitatively modeled based on measured sediment properties (10-50 kHz). Third, measure sediment attenuation (10-300 kHz) and sound speed (10-300 kHz) and determine constraints imposed on sediment acoustic models, such as poroelastic (Biot) models. Fourth, obtain measures of acoustic spatial and temporal coherence within the sediment and demonstrate that these quantities can be quantitatively modeled based on measured sediment properties (10-50 kHz). Fifth, measure backscattering levels from buried objects in order to test buried-object-detection (10-50 kHz) modeling accuracy.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2002</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2002 to 00-00-2002</b>	
4. TITLE AND SUBTITLE <b>High-Frequency Sound Interaction in Ocean Sediments</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Applied Physics Laboratory, University of Washington, Seattle, WA, 98105</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>Our long-term goal is to develop accurate models for high-frequency scattering from, penetration into, and propagation within shallow water sediments. Reaching this goal requires a better understanding of several fundamental issues pertinent to high-frequency sediment acoustics. These issues include an understanding of the dominant scatterers versus frequency near the sediment surface, the potential need for poroelastic sediment models, the appropriateness of stochastic descriptions of sediment heterogeneities, the importance of single versus multiple scattering in sediments, and an understanding of the physical and biological processes that determine sediment structure.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## **APPROACH**

The objectives are being addressed as part of the ONR High-Frequency Sediment Acoustics Departmental Research Initiative (DRI). An experiment, designated SAX99 (Sediment Acoustics Experiment - 1999), was carried out from late September to mid November 1999. The site was near Fort Walton Beach, Florida, and was chosen to give a relatively high critical grazing angle (about  $30^\circ$ ), with a goal of a single sediment type (in this case medium sand) down to the maximum acoustic penetration depths of interest (of order 1 m). The water depth was about 18 m, chosen deep enough to permit backscattering measurements to be made at relatively low grazing angles, but shallow enough to allow diver installation of instrumentation within the sediment and to allow diver sampling of sediment properties. A well-defined ripple field was present at the SAX99 site. The ripple wavelength was about 50 cm, and the amplitude varied during the course of the experiment, but was typically 3-5 cm (peak-to-trough).

SAX99 was a collaborative effort involving many investigators. Chotiros (ARL-UT), Holliday (BAE SYSTEMS, formerly Tracor), Greenlaw (BAE), McGehee (BAE), Lopes (CSS), Christoff (CSS), and Commander (CSS) made acoustic scattering and/or penetration measurements similar or complimentary to ours [1]. The physical properties and biological processes of the sediment and water column were examined in detail as described by Richardson et al. [2]. The results of this work provide the information needed to numerically simulate the acoustic measurements, an important step in improving our understanding of the acoustic processes under study.

## **WORK COMPLETED**

Analysis of the extensive data sets gathered during SAX99 has been largely completed. Bottom backscattering strengths have been obtained at frequencies of 20-300 kHz and grazing angles of  $10^\circ$ - $40^\circ$ . Acoustic penetration data at 11-50 kHz have been analyzed to quantitatively describe the penetration at grazing angles of  $10^\circ$ - $40^\circ$ , extending well below the critical angle of about  $30^\circ$ . For the penetration data set, the azimuthal angle of the incidence field varied over  $160^\circ$  to show effects of the directionality of the ripple field. Measurements were also made at several values of the ripple amplitude.

During SAX99 APL-UW deployed three systems capable of making sound speed and attenuation measurements, and several other researchers made additional measurements. These measurements have now been largely analyzed. Together, the data for sound speed spanned the frequency range of about 100 Hz to 400 kHz, and for attenuation the frequency range of 10 kHz to 400 kHz. The data are unique both for the frequency range spanned at one site and for the extensive environmental characterization that was carried out as part of SAX99. Environmental measurements were sufficient to determine most of the parameters for the Biot poroelastic model of the sediment and to restrict the range of values for the remaining parameters, setting the stage for tests of Biot model predictions of the frequency dependence of sound speed and attenuation.

Substantial progress has also been made using the environmental measurements of APL-UW, NRL-SSC, and others in modeling SAX99 acoustic results in order to fully quantify the acoustic processes under investigation. As part of this work, two new bottom scattering models were developed. Traditionally, a fluid description of the sediment has been used together with rough surface perturbation theory to model backscattering from sediment roughness [3]. However, for

given roughness conditions the backscattering level may provide an additional test of the applicability of Biot theory to sediment acoustics. Previously, Biot model predictions for backscattering strength based on rough surface perturbation theory were not available in the literature. Thus, a first step in the modeling process was to develop the theory for backscattering based on a Biot model for the sediment. A paper on this topic has been accepted for publication in the J. Acoust. Soc. Am [4].

The Biot model of sediment acoustics is well known for its complexity, and it is therefore of high interest if simplifications can be made to the backscattering model based on the Biot sediment description. One of us [K. L. Williams] has indeed found such a simplification which yields essentially the same backscattering (and bistatic) predictions as obtained with the full Biot sediment description. In this new approach, scattering theory appropriate for a rough interface separating water and a fluid sediment is used, but an “effective density” fluid sediment model is employed to capture the essential features of the poroelastic description. Frequency dependent values for sound speed, attenuation, and an effective density of the sediment are all derived using an unconsolidated limit of Biot theory. A paper on this topic has been accepted for publication in the J. Acoust. Soc. Am [5].

Finally, two pieces of APL-UW equipment were used for *in situ* measurements of sediment heterogeneity during SAX99: a sediment conductivity probe system, and an acoustic tomographic system. Initial analysis of data from the conductivity probe (known as IMP for In-situ Measurement of Porosity) has been used to investigate the correlation between porosity heterogeneity and sediment roughness. In addition, the conductivity probe has proven to be a reliable instrument for obtaining bottom roughness data. Since the instrument covered 1 m-long tracks, the roughness data obtained from it complement rough surface data collected by other means, such as stereo photogrammetry. Analysis of SAX99 data from the acoustic tomographic system (known as AI for High Resolution Sediment Acoustic Imager) remains ongoing.

## RESULTS

Rough surface backscatter predictions for the Biot model and the effective density fluid model (EDFM) are found to be about 2 to 3 dB lower than for the standard sediment fluid model (FM) for the frequencies used and conditions encountered during SAX99. In principle, this allows us to test whether the Biot sediment description is superior to the fluid description for modeling backscatter. Such a test requires very accurate estimates of the sediment roughness spectrum, a key input to the backscatter models. We have found through examination of stereo photogrammetric roughness data and of sediment conductivity probe roughness data that sediment roughness at the SAX99 site shows evidence of spatial non-stationarity. This observation increases the uncertainty bounds we must place on our model for the sediment roughness spectrum, since the roughness measurements could not be made at the same location as the backscattering measurements and they extended over much smaller regions compared to the area contributing to backscatter. As a result, we find the roughness spectrum uncertainty to be roughly  $\pm 2$  dB, which is uncomfortably large when looking for a 2 to 3 dB effect. Nevertheless, the acoustic backscatter data is found to be much more consistent with the Biot model (and thus the EDFM also) than with the FM.

To summarize the results of backscatter data/model comparisons, it is convenient to identify three frequency regimes: 20 to 50 kHz, 50 to 150 kHz, and 150 to 300 kHz. The sediment roughness is

characterized over the entire range, but due to measurement resolution the sediment volume heterogeneity is characterized only over the 20 to 50 kHz range. In this frequency regime, the model results show that rough surface scattering dominates sediment volume scattering by a wide margin (10 to 20 dB). The backscatter data also agree closely in level to rough surface model results, with both showing a dip in level just above the critical angle of  $30^\circ$ . These comparisons lead to the conclusion that, at the SAX99 site, surface roughness is the dominant cause of backscattering in the frequency range from 20 to 50 kHz for the grazing angles examined (all less than  $40^\circ$ ). Data/model comparisons lead to the further conclusion that, for 20 to 50 kHz, the Biot model and the EDFM are better predictors of measured scattering strengths than the FM.

In the 50 to 150 kHz range the backscatter data below  $30^\circ$  continue to agree with the model results. However, for much of the data in this range a drop in backscattering above  $30^\circ$  is not evident. At this stage, volume heterogeneity scattering has only been included within the FM model. When measured volume heterogeneity spectra are extrapolated to allow modeling of volume scattering in this regime, the backscatter drop above  $30^\circ$  is still present in disagreement with data, possibly indicating higher volume heterogeneity at these smaller spatial scales than found by extrapolation. At 300 kHz measured backscatter is significantly higher in the region below  $30^\circ$  grazing in comparison to model results based on rough surface scattering alone. This suggests that in the 150 to 300 kHz range the dominant scattering mechanism has transitioned from surface roughness to some other mechanism. One possibility is that shell pieces lying at the sediment/water interface are becoming significant contributors to the backscattering.

Analysis of SAX99 acoustic penetration data and comparisons with simulations have shown conclusively that scattering from large-scale sediment ripple is the dominant mechanism for subcritical penetration. In this analysis, penetration data from the APL-UW buried array have been used to produce speed-angle plots [6], and simulations of these plots have been made using perturbation theory to account for scattering at the sediment surface. A deterministic 1-D ripple model was estimated based on ripple wavelength (48 cm) and height (1 cm rms) determinations from conductivity probe data, and ripple phase and azimuth were estimated from diver video taken at the site of the buried array. For geometries with subcritical grazing angles, simulations show that no significant energy reaches the buried array via refracted paths; instead, scattering from the sediment ripple is responsible for the penetration. We believe the excellent correspondence between measured and simulated speed-angle plots shows conclusively that the same interpretation carries over to the measurements as well.

To see simply the effect of sediment ripple on penetration, consider the ripple to be represented by a monochromatic sine wave, take the direction of the incident wave to be perpendicular to the ripple crests, and ignore attenuation. Then the effect of the ripple with wave vector  $\mathbf{K}_r$  in a perturbation analysis is to scatter an incident plane wave in the water with horizontal wave vector  $\mathbf{K}_i$  into a transmitted plane wave with horizontal wave vector  $\mathbf{K}_2 = \mathbf{K}_i - \mathbf{K}_r$ . This leads to a depression angle  $\theta_2$  for the scattered wave given by

$$\cos\theta_2 = (c_2/c_1) [\cos\theta_1 - \lambda_1/\lambda_r], \quad (1)$$

where  $c_2/c_1$  is the sediment/water sound speed ratio,  $\theta_1$  is the incident grazing angle,  $\lambda_1$  is the acoustic wavelength in water, and  $\lambda_r$  is the ripple wavelength. For the SAX99 parameters  $c_1 = 1530$  m/s and  $c_2 = 1775$  m/s with  $\theta_1 = 21.4^\circ$ , one finds  $\theta_2 = 26.5^\circ$  for 20 kHz,  $16.9^\circ$  for 30 kHz, and  $9.0^\circ$  for 40 kHz. At 50 kHz (1) gives  $\cos\theta_2 > 1$ ; in other words, the first-order scattered wave has become evanescent

leading to a “cutoff” above 40 kHz, observed in both the data and in full simulations. In fact, the trends in both the data and simulations are in remarkably good agreement with this simple model. (Eq. (1) also shows the cutoff will occur when the ripple wavelength is increased.) These results further strengthen the finding that scattering from large-scale ripple was the dominant penetration mechanism during SAX99.

Finally, Biot model predictions have been compared with the measured frequency dependence of sound speed and attenuation. The results indicate that the variation of sound speed with frequency is well modeled by Biot theory, but the variation of attenuation with frequency deviates from Biot theory as the frequency increases. The measured attenuation is found to increase approximately linearly with frequency, while Biot model predictions rise more slowly, and the discrepancy is especially pronounced above 100 kHz. Examination of the received waveforms has led to the hypothesis that this deviation may be due to increased volume scattering at high frequencies that is not accounted for in the present version of Biot theory.

## **IMPACT/APPLICATIONS**

Work under this program should lead to improved high-frequency models for acoustic scattering from sediments, for penetration into sediments, and for spatial and temporal coherence within sediments. These improvements should have an impact on modeling the detection and classification of buried objects. A corollary to acoustic model refinement should be a better understanding of the essential parameters that are needed for practical models. In the near term, SAX99 will provide a well-characterized environment that can be used to test modeling accuracy for applied measurements.

## **RELATED PROJECTS**

Investigators for a large number of related projects were represented in SAX99 [1,2]. In particular, Christoff and Commander from CSS deployed a synthetic aperture sonar system operating at 20 kHz and obtained subcritical buried target detections. In addition, the following related projects can be noted:

Tang, Williams, and Thorsos will be using a second generation conductivity probe system (IMP-2) to measure sediment roughness, including large-scale ripple, in support of CSS acoustic penetration and buried target measurement during FY02-03.

Lim at CSS has been developing techniques for modeling acoustic scattering from buried targets. In particular, he has included the effects of sediment interface roughness in coupling acoustic energy into the sediment when it is incident at subcritical grazing angles. This work is relevant to understanding SAX99 measurements of scattering from buried targets.

Jumars (U. of Maine) and Jones (APL-UW) are developing a measurement facility to study the effects of benthic biological activity on high-frequency acoustic backscattering. These experiments would be conducted in a more controlled environment than was the case for SAX99.

## REFERENCES

1. E. I. Thorsos, K. L. Williams, N. P. Chotiros, J. T. Christoff, K. W. Commander, C. F. Greenlaw, D. V. Holliday, D. R. Jackson, J. L. Lopes, D. E. McGehee, M. D. Richardson, J. E. Piper, and D. Tang, "An overview of SAX99: Acoustic measurements," *IEEE J. Ocean. Eng.* **26**, 4-25(2001).
2. M. D. Richardson et al., "Overview of SAX99: Environmental considerations," *IEEE J. Ocean. Eng.* **26**, 26-54(2001).
3. D. R. Jackson, K. B. Briggs, K. L. Williams, and M. D. Richardson, "Tests of models for high-frequency seafloor backscatter," *IEEE J. Ocean. Eng.* **21**, 458-470 (1996).
4. K. L. Williams, J. M. Grochocinski, and D. R. Jackson, "Interface scattering by poroelastic seafloors: First-order theory," accepted for publication in *J. Acoust. Soc. Am.*
5. K. L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," accepted for publication in *J. Acoust. Soc. Am.*
6. E. I. Thorsos, D. R. Jackson, and K. L. Williams, "Modeling of subcritical penetration into sediments due to interface roughness," *J. Acoust. Soc. Am.* **107**, 263-277 (2000).

## PUBLICATIONS

- E. I. Thorsos, K. L. Williams, N. P. Chotiros, J. T. Christoff, K. W. Commander, C. F. Greenlaw, D. V. Holliday, D. R. Jackson, J. L. Lopes, D. E. McGehee, M. D. Richardson, J. E. Piper, and D. Tang,, "An overview of SAX99: Acoustic measurements," *IEEE J. Ocean. Eng.* **26**, 4-25 (2001).
- M. D. Richardson et al., "Overview of SAX99: Environmental considerations," *IEEE J. Ocean. Eng.* **26**, 26-54 (2001).
- F. D. Hastings, J. B. Schneider, S. L. Broschat, and E. I. Thorsos, "An FDTD method for analysis of scattering from rough fluid-fluid interfaces," *IEEE J. Ocean. Eng.* **26**, 94-101 (2001).
- K. L. Williams, J. M. Grochocinski, and D. R. Jackson, "Interface scattering by poroelastic seafloors: First-order theory," accepted for publication in *J. Acoust. Soc. Am.*
- K. L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," accepted for publication in *J. Acoust. Soc. Am.*
- M. D. Richardson, K. L. Williams, K. B. Briggs, and E. I. Thorsos, "Dynamic measurements of sediment grain compressibility at atmospheric pressure: acoustic applications," submitted to *IEEE J. Ocean Eng.*
- E. I. Thorsos, K. L. Williams, D. R. Jackson, M. D. Richardson, K. B. Briggs, and D. Tang, "An experiment in high-frequency sediment acoustics: SAX99," in *Proceedings of the Institute of Acoustics* **23**, 344-354 (2001).

D. R. Jackson and M. D. Richardson, “Seasonal temperature gradients within a sandy seafloor: implications for acoustic propagation and scattering,” in *Proceedings of the Institute of Acoustics* **23**, 361-368 (2001).

K. L. Williams, M. D. Richardson, K. B. Briggs, and D. R. Jackson, “Scattering of high-frequency energy from discrete scatterers on the seafloor: Glass spheres and shells,” in *Proceedings of the Institute of Acoustics* **23**, 369-374 (2001).

K. B. Briggs, K. L. Williams, M. D. Richardson, and D. R. Jackson, “Effects of changing roughness on acoustic scattering: (1) natural changes,” in *Proceedings of the Institute of Acoustics* **23**, 375-382 (2001).

M. D. Richardson, K. B. Briggs, K. L. Williams, A. P. Lyons, and D. R. Jackson, “Effects of changing roughness on acoustic scattering: (2) anthropogenic changes,” in *Proceedings of the Institute of Acoustics* **23**, 383-390 (2001).